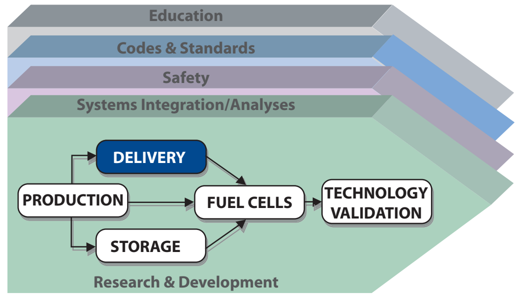
3.2 Hydrogen Delivery

Hydrogen must be transported from the point of production to the point of use. It also must be handled and moved within refueling stations or stationary power facilities. Due to its relatively low volumetric energy density, transportation and final delivery to the point of use can be one of the significant costs and energy inefficiencies associated with using hydrogen as an energy carrier.



3.2.1 Technical Goal and Objectives

Goal

Develop hydrogen fuel delivery technologies that enable the introduction and long-term viability of hydrogen as an energy carrier for transportation and stationary power.

Objectives

- By 2006, define a cost-effective and energy-efficient hydrogen fuel delivery infrastructure for the introduction and long-term use of hydrogen for transportation and stationary power.
- By 2010, develop enabling technologies to reduce the cost of hydrogen fuel delivery from central and semicentral production facilities to the gate of refueling stations and other end users to <$0.70/kg.
- By 2010, develop enabling technologies to reduce the cost of moving and handling hydrogen within refueling stations and stationary power facilities to a vehicle or stationary power unit to <$0.60/kg.
- By 2015, develop enabling technologies to reduce the cost of hydrogen fuel delivery from the point of production to the point of use in vehicles or stationary power units to <$1.00/kg in total.

3.2.2 Technical Approach

The Hydrogen Delivery program element is focused on meeting the hydrogen delivery objectives outlined in Section 3.2.1 by conducting R&D through industry, national laboratory, and university projects. Projects will address the barriers outlined in Section 3.2.4.2, and progress toward meeting the objectives will be measured against the technical targets outlined in Section 3.2.4.1.

Infrastructure Options

The hydrogen production strategy greatly affects the cost and method of delivery. If the hydrogen is produced centrally, the transport distances increase cost significantly. It can be produced semicentrally (within 100 miles of the point of use) to reduce this distance and the related costs. Distributed production at the point of use eliminates the transportation costs but results in higher production costs because the economy of larger scale production is lost.

Hydrogen can be transported as a gas at low (100–300 psig) or high (3000–5000 psig) pressure or as a cryogenic liquid. It can be transported by gas pipelines, gas or cryogenic liquid trucks, tube trailers, barge, or rail cars. The hydrogen currently in the marketplace for industrial use is delivered by one of these methods, as illustrated in Figures 3.2.1–3.2.2.

Figure 3.2.1. Hydrogen Delivery via Pipeline

Figure 3.2.2. Compressed Hydrogen Delivered via Tractor Trailer

Higher energy density carriers such as natural gas, methanol, ethanol, or other liquids derived from fossil fuels or renewable biomass can be produced, transported to the point of use, and reformed to hydrogen. There is also the possibility of using materials such as metal hydrides or other hydrogen containing solids or liquids that can be treated to release hydrogen when needed at a refueling station or stationary power location or directly on a vehicle.

One advantage of hydrogen is that it can be produced from a variety of feedstocks in a variety of ways. It is likely that it will be produced from a spectrum of feedstocks and production technologies over the course of its introduction and long-term use as a primary energy carrier. Similarly, the transportation technology may well encompass several options over the short and long terms. The transportation methods used at the early stages, when volumes are relatively low, may be different than those used when it is well established and used in large quantities as a primary energy carrier. At very large volumes, an extensive pipeline infrastructure will likely be the most cost-effective manner to deliver hydrogen to much of the market as is done with natural gas today. However, other methods, such as distributed natural gas or liquid reforming, will be needed for the transition period. Lower cost and more energy-efficient technologies are needed for hydrogen transportation and handling.

Analysis

One of the first tasks of the Hydrogen Delivery program element will be to perform an analysis to help define a cost-effective, energy-efficient, and safe hydrogen fuel delivery infrastructure for the introduction and long-term use of hydrogen for transportation and stationary power. This analysis will be used to guide future R&D, focusing future efforts on several but fewer options.

Compression and Liquefaction

Compression and liquefaction of hydrogen have significant costs and energy requirements (see Table 3.2.1). Compression will be a key operation in the future hydrogen economy in any foreseen scenario of hydrogen production and delivery options. Liquefaction will likely play a role in the introduction period and in situations where lower volumes are needed.

Pipelines

Hydrogen delivery by pipeline is currently the lowest cost delivery option at high volumes. However, a large capital investment is required to expand the very limited existing hydrogen pipeline infrastructure to the level that would be necessary if hydrogen were to become the primary energy carrier. Using existing natural gas pipelines to transport hydrogen is an option that will be evaluated to reduce the investment required. It may be possible to mix up to ~30% hydrogen with natural gas in the existing natural gas pipeline infrastructure without modifications to the pipeline. This mode would require cost-effective technology to separate pure hydrogen at its point of use. The possibility of upgrading the natural gas pipeline for pure hydrogen use will also be examined.

New Solid/Liquid Carriers

New technologies to increase energy density for hydrogen transport will be explored and developed for possible delivery cost breakthroughs. This includes the use of innovative solid or liquid hydrogen carriers that can release hydrogen at its point of use without significant processing. Metal hydrides and other more novel approaches will be evaluated.

Interface with Hydrogen Storage

The technology selected for storing hydrogen on-board vehicles may affect the hydrogen delivery system and infrastructure. Delivery and on-board storage need to be integrated at some junction in the system. This could prove to be very simple. For example, the on-board storage system could be a solid carrier that receives hydrogen gas directly from a dispenser at a refueling station. On the other hand, if on-board liquid hydrogen or an on-board carrier system requiring off-board regeneration is selected, the hydrogen delivery system will need to cost-effectively accommodate the approach. The Hydrogen Delivery milestone chart in Section 3.3.6 and the Hydrogen Storage milestone chart in Section 3.4.6 show several inputs and outputs between the Delivery and Storage program elements that address these interactions.

To a lesser degree, the off-board hydrogen storage and delivery research also need to be integrated. This integration is also reflected in the milestone chart inputs and outputs in the Delivery and Storage program elements.

Federal Funding Profile

This focused effort on hydrogen delivery is a new program element. It is a key enabler to a hydrogen economy. It is expected that funding will ramp up quickly, as necessary, to overcome the technology barriers and achieve the objectives. The results of the initial analysis task will focus the program on the areas of research that should be supported with federal funding, aimed at achieving the 2015 delivery cost reduction objective. After 2015, the remaining federal effort will likely be selective and only fund new concepts that could make further significant impacts on delivery costs or energy efficiencies.

3.2.3 Programmatic Status

There has not been a specific focus on hydrogen transportation and delivery in the Hydrogen, Fuel Cells, and Infrastructure Technologies Program. The importance of this part of the value chain was highlighted in the National Hydrogen Energy Roadmap published in the fall of 2002. The Hydrogen Delivery program element is now being initiated. The current projects that pertain to this program element are shown in Table 3.2.1.

Table 3.2.1 Current Hydrogen Delivery Projects

Challenge	Approach	Activities
Reduce the cost and improve the energy efficiency of gaseous hydrogen compression.	• Develop novel compression technologies • Incorporate technological improvements in hydrogen compression to reduce costs and improve efficiency.	• **Ergenics:** Novel compression technology using reversible metal hydride hydrogen adsorption/desorption cycle. • **Praxair, UOP/Sun Line:** Exploring recent advances in hydrogen compression for use in refueling station validation projects involving compression and storage.

Research and development (R&D) of metal hydrides and other solid or liquid chemical or physical carriers of hydrogen useful for storage (See Section 4.3, Hydrogen Storage) may also find use for hydrogen transportation.

3.2.4 Technical Challenges

Cost and Energy Efficiency

The overarching technical challenge for hydrogen delivery is reducing the cost of the technology. The energy efficiency of delivery also needs to be improved.

Current estimates of the cost of long-distance transport and handling of hydrogen from the point of production to the refueling unit range from \$3.00-\$6.00/kg of hydrogen, depending on the distance and method. The goal for the cost of delivered hydrogen is \$1.50/kg—delivered, untaxed—at the pump by 2010.

Lack of Infrastructure

A hydrogen production and delivery infrastructure suitable to support hydrogen fuel cell vehicles does not currently exist. Small-scale distributed production of hydrogen from natural gas or liquid fuels at refueling facilities is a possible approach, but current costs are too high, and distributed production of hydrogen alone will not meet the needs for a hydrogen energy infrastructure. Central or semicentral production of hydrogen can significantly reduce production costs. Lower cost hydrogen fuel delivery technology is needed to enable the establishment of a hydrogen infrastructure.

Infrastructure Trade-Offs

Options and trade-offs for hydrogen delivery from central and semicentral production to the point of use are not well understood. Analysis is needed to understand the advantages and disadvantages of the various energy sources and production/delivery technology options to guide research and investment efforts for the ultimate hydrogen delivery infrastructure and for the most appropriate infrastructure to be used during the introduction of hydrogen as a primary energy carrier. Examples of some of these trade-offs include:

- Centrally producing a liquid fuel, such as ethanol from biomass, and then transporting this relatively high energy density fuel to a refueling station for reforming into hydrogen versus centrally producing hydrogen via biomass gasification and then transporting the lower energy density hydrogen to the refueling station.
- Utilizing liquefaction and liquid truck delivery during the early transition period at low hydrogen demand rates versus installing some hydrogen delivery pipelines early—the former involves potentially less capital risk while the latter sets the stage for the longer term, lower cost delivery option when hydrogen is in high demand.
- The cost of a metal hydride delivery system without the need for compression versus the cost of gaseous delivery with compression.

3.2.4.1 Technical Targets

Table 3.2.2 lists the technical targets for the Hydrogen Delivery program element. Targets for 2010 are R&D milestones for measuring progress toward the ultimate goal of establishing a hydrogen infrastructure.

The key to achieving the overall cost objectives of the Hydrogen Delivery program element is to bring down the costs and improve the energy efficiency of the key delivery technologies; compression, liquefaction, and pipelines. The targets shown in Table 3.2.2 are based on a preliminary analysis of current technology and costs, estimates of what might be possible with technology advances, initial estimates of total delivery system costs, and the key cost elements that must be reduced to meet the overall cost objectives. Delivery costs are a complex function of the technology, delivery distance, system architecture, and hydrogen demand. Much more analysis needs to be done to better refine the targets listed in Table 3.2.2. This analysis will be the first key task of the delivery program effort.

Preliminary targets are also given for possible hydrogen solid- or liquid-carrier technology that might prove useful for hydrogen delivery. The targets are based on current knowledge about the potential of these technology options for on-board hydrogen storage systems. An analysis of the cost of such systems in a delivery infrastructure have not yet been completed.

Table 3.2.2. Hydrogen Delivery Targets[a]

Delivery Method	Target	2003 Status	2005 Target	2010 Target
Gaseous Hydrogen Compression[b]	Cost ($/kg of hydrogen) Energy Efficiency (%) (LHV)	$0.18 90%	$0.17 92%	$0.14 95%
Hydrogen Liquefaction	Cost ($/kg of hydrogen) Energy Efficiency (%) (LHV)	$1.10 65%	$1.00 70%	$0.53 87%
Hydrogen Gas Pipelines	Trunk Lines[c] ($/mile) Distribution Lines[d] ($/mile)	$1.4M $600k	$1.2M $500k	$600k $350k
Hydrogen Carrier Technology[e]	Hydrogen Content (% by Wt.) Hydrogen Content (kg of hydrogen/M^3) Energy Efficiency (%) (LHV)	3% 45 80%	6.5% 97 82%	10% 150 85%

[a]This table is based on work and analysis performed at NREL and summarized in the report "Costs of Storing and Transporting Hydrogen," Wade Amos, November 1998, NREL/TP-570-25106. This information was used to arrive at the current (2003) targets and used to project what might be feasible and is necessary to achieve the objectives of the program. Analysis in this area at NREL and on-going research efforts have been factored into this table. Energy efficiencies based on lower heating values (LHVs).
[b]Based on compression of hydrogen from 1 atm. to 3,000 psig.
[c]Based on the capital requirements for 12 inch lines.
[d]Based on the capital requirements for 4 inch lines.
[e]The 2003 values given are based on metal hydride technology. The future targets are based on what is required to achieve the program objectives. These targets might be achieved by a variety of carrier technologies that are being or might be researched.

3.2.4.2 Barriers

A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis. Options and trade-offs for hydrogen/carrier delivery from central and semicentral production to the point of use are not well understood. Distributed production is another option. Analysis is needed to understand the advantages and disadvantages of these various approaches. Many site-specific and regional issues are associated with integrating production and use of hydrogen. Production and delivery systems need to be integrated to minimize cost and take full advantage of local resources and situations.

B. High Costs of Hydrogen Compression. Hydrogen gas has a low volumetric energy density, especially at low pressures. Hydrogen compression is costly and energy intensive. Low-cost, efficient compression technologies are needed.

C. High Costs of Hydrogen Liquefaction. Hydrogen liquefaction is costly and energy intensive. Low-cost, efficient liquefaction technologies are needed.

D. High Capital Cost of Pipelines. Existing hydrogen pipelines are very limited and not adequate to broadly distribute hydrogen. Building new pipelines requires a large capital investment and may entail costly acquisition of land rights. Development of innovative materials and technologies (seals, components, sensors, and safety and control systems) is needed to reduce cost. Approaches for using existing natural gas pipelines to transport mixtures of natural gas and hydrogen without hydrogen embrittlement and leakage need to be explored, and technologies for separating hydrogen from natural gas need to be developed. The possibility of utilizing or upgrading natural gas pipelines for pure hydrogen use also needs to be examined.

E. Solid and Liquid Hydrogen Carrier Transport. Solid or liquid carriers that can release hydrogen without significant processing operations are possible options for hydrogen transport. Current solid and liquid hydrogen transport technologies have high costs, insufficient energy density, and/or poor hydrogen release and regeneration. Step change improvements in current technologies or new technologies are needed.

F. Transport Storage Costs. Hydrogen storage at production facilities,refueling stations, and other points of end use; surge capacity for pipelines, trucks, and rail at terminals; cryogenic transport and storage; and liquid and gas transport containers for truck and rail are costly. Technologies need to be developed to reduce these costs.

3.2.5 Technical Task Descriptions

The technical task descriptions are presented in Table 3.2.3. Concerns regarding safety and environmental effects will be addressed within each task in coordination with the appropriate program element. The duration of a task and the barriers associated with it (see Section 3.2.4.2) appear after the task title.

Table 3.2.3. Technical Task Descriptions

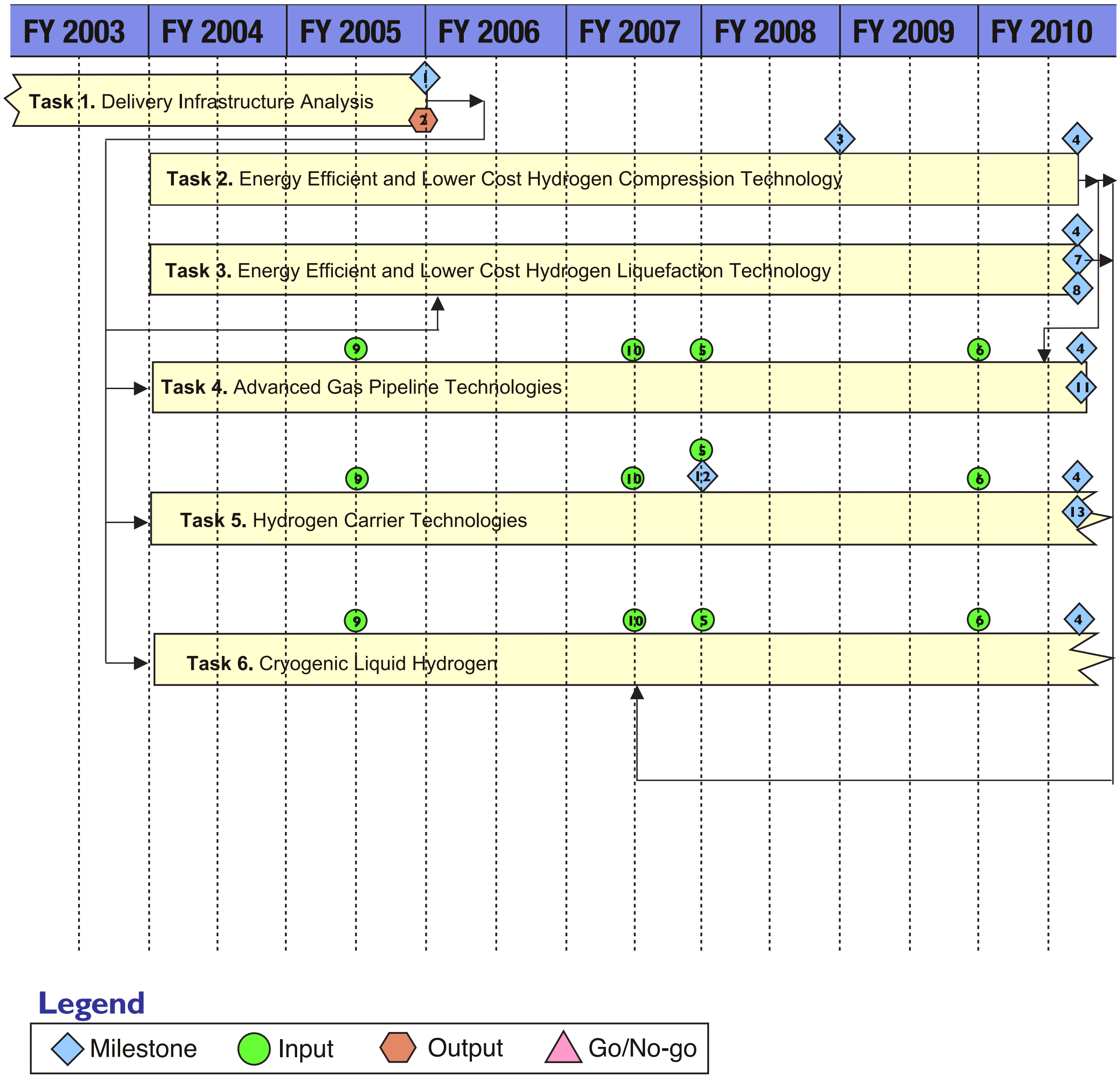
Task	Description	Duration/Barriers
1	**Delivery Infrastructure Analysis** • Perform an analysis to define a cost-effective, energy-efficient and safe hydrogen fuel delivery infrastructure for the introduction and long-term use of hydrogen for transportation and stationary power.	8 Quarters/Barrier A
2	**Develop Energy-Efficient and Lower Cost Hydrogen Compression Technology** • Examine improved or alternative compression head designs, technology to increase suction pressure, and technology to capture interstage heat.	20 Quarters/Barrier B

3	**Develop Energy-Efficient and Lower Cost Hydrogen Liquefaction Technology** • Investigate cost and energy efficiency gains for larger scale operations, achieving additional energy integration, and improving refrigeration schemes. • Explore new and novel breakthrough technologies such as magnetic-caloric liquefaction.	28 Quarters/Barrier C
4	**Advanced Gas Pipeline Technologies** • Devise lower cost pipeline installation technologies and approaches. • Develop lower cost materials, seals, components, sensors, and controls. • Analyze, investigate, and develop existing natural gas pipelines for transporting hydrogen and natural gas mixtures (including technology to cost-effectively separate the hydrogen) and upgrading the natural gas pipeline for pure hydrogen.	28 Quarters/Barrier D
5	**Hydrogen Carrier Technologies** • Develop breakthrough chemical or physical hydrogen carrier technologies for high energy density, low-cost transport of hydrogen.	28+ Quarters/ Barriers B, C, D, E, F
6	**Cryogenic Liquid Hydrogen** • Develop breakthrough technology for lower cost cryogenic liquid hydrogen handling and transport.	28+ Quarters/ Barriers B, C, D, E, F
Note: The total duration of the program planning period is 32 quarters; tasks that begin before this period or continue beyond it do not reflect durations outside the planning period.		

3.2.6 Milestones

Figure 3.2.3 shows the interrelationship of milestones, tasks, supporting inputs from other program elements, and technology program outputs for the Hydrogen Delivery program element from FY 2004 through FY2010. This information is also summarized in Table B.2 in Appendix B.

Figure 3.2.3. Hydrogen Delivery R&D Network



For chart details see next page.

1. Complete definition of a cost-effective hydrogen fuel delivery infrastructure to support the introduction and long-term use of hydrogen for transportation and stationary power.
2. Output to Hydrogen Storage: Assessment of cost-competitive off-board storage requirements
3. Verify 20% cost reduction for hydrogen compression.
4. Define technology-feasible routes and approaches for hydrogen fuel delivery (gate to refueling unit) for a cost of less than \$1/kg.
5. Input from Hydrogen Storage: Initial downselect of on-board storage system
6. Input from Hydrogen Storage: Final downselect of on-board storage system
7. Verify 50% cost reduction for hydrogen liquefaction.
8. Increase the energy efficiency of hydrogen liquefaction from 65% to 87%.
9. Input from Safety: Safety requirements and protocols for pipelines and transit
10. Input from Hydrogen Storage: Bulk off-board storage technology for fueling stations and delivery
11. Verify reduction of the capital cost of hydrogen pipelines by 50%.
12. Verify the feasibility of hydrogen carrier systems with 10% hydrogen by weight.
13. Verify the feasibility of a hydrogen carrier system that could achieve a cost of <\$0.70/kg of hydrogen for hydrogen transport distances of 100 miles or less.